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Development of Eco-friendly Self-compacting Concrete Using Fly Ash and Waste Polyethylene Terephthalate Bottle Fiber

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Abstract

This study aims to utilize fly ash and waste PET bottles for producing more sustainable self-compacting concrete (SCC) with better mechanical strength. Fly ash is utilized as a supplementary cement material and waste PET bottles as fiber reinforcement to improve its flexural strength and achieve the targeted compressive strength. The experimental works were conducted on eight variations using 80 specimens, divided into two main groups of partial cement replacement using 0% and 15% fly ash by weight. The two variants are added with PET fiber based on the volume fractions of 0%, 0.25%, 0.50%, and 0.75%. Fresh concrete was tested using the slump flow method (T50) and the Visual Stability Index (VSI) based on ASTM 1611. The hardened concrete tests are conducted after 56 days and include testing the concrete's compressive strength, flexural strength, and ultrasonic pulse velocity. Test results showed that the presence of PET fiber in the SCC mix decreased its flowability. However, when added up to 0.75%, the mixes still meet the flowability requirements of fresh-state SCC. PET fiber addition tends to reduce the compressive strength, whereas the reduction in compressive strength of SCC with PET fiber without fly ash is insignificant. However, in SCC that uses fly ash, the addition of PET fiber causes a significant decrease in its compressive strength. Adding PET fiber into SCC mixes can increase flexural strength, both for the two variants: SCC without fly ash and SCC with fly ash. It can be concluded that PET waste fiber with an aspect ratio of 40 can be added up to 0.5% for SCC without fly ash and up to 0.25% by volume fraction for SCC with fly ash addition. The ultrasonic pulse velocity test results have an excellent tendency to predict the concrete's compressive and flexural strengths. Therefore, the UPV test can be applied for the non-destructive test evaluation of PET fiber-reinforced SCC.

Keywords: Compressive Strength; Flexural Strength; Fly Ash; Polyethylene Terephthalate; Self-Compacting; Ultrasonic Pulse Velocity.

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1. Introduction

Self-compacting concrete (SCC) is a special concrete with excellent flowability, passing ability, and self-compacting ability with a minimum risk of segregation. It should be able to flow and spread into empty spaces to fill the formwork with its self-weight. These fresh concrete characteristics must be achieved to ensure excellent quality in concrete works, especially in conditions with dense reinforcements. SCC should be able to fill the concrete formwork and then perfectly bond with the rebar without any compaction work. Developing SCC mixes requires carefully considering several vital aspects, such as 1) increasing fine aggregate with consequently less fraction of coarse aggregate, 2) lower water/powder ratio, 3) using proper superplasticizer, and 4) increasing binder content using Portland cement incorporated with fine powder materials. These combined materials are needed to compose a binder that can control the homogeneity of fresh concrete and achieve easy-flowing but viscous characteristics [1–4].

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SCC provides some significant benefits in concrete construction work, such as 1) minimizing required compaction in concreting work, 2) speeding up construction time and therefore minimizing labor costs, 3) reducing the crowd in the workspace and reducing noise at the construction site, 4) avoiding construction defects, such as concrete pores and honeycombing, 5) ensuring concrete density for hard-to-reach locations using vibrators or any other type of compactor, and 6) improving homogeneity and overall structure performance. These benefits led to the broader use of SCC for concrete works [5, 6].

SCC production employs a larger binder quantity. The price of Portland cement is relatively higher than other required concrete materials. Therefore, it is necessary to look for potential substitute materials as alternatives that should be environmentally friendly and vastly available at an affordable price [7–11]. Previous researchers have attempted to utilize various waste materials in SCC mixtures that are more environmentally friendly as Supplementary Cement Materials (SCMs). These eco-friendly materials can modify the properties of fresh concrete since SCMs in SCC may fill the pores and lower the pore water content. The increased specific surface area of some finely ground materials will improve water absorption and decrease free water content. The SCMs also affect the mechanical strength due to the filler effect, the pozzolanic reaction, and the dilution effect. These mineral admixtures can come from minerals that require minimal fossil fuels and carbon emissions in the production or even utilize industrial by-product materials [9-11] or those derived from plantation, agricultural, or forestry product wastes [12-15].

Coal consumption in Indonesia is dominated by around 80 percent of electric power plants, and the remaining 20 percent is used by industries such as cement and fertilizers. In 2021, domestic coal consumption was approximately reaching 137.5 million tons. Assuming the coal ash waste in the form of fly ash and bottom ash is produced at around 5%, the waste generated reaches 6.875 million tons annually. The composition of fly ash is dominated by ferrous, alumina, silica, and CaO, reaching 70–90% of the total weight. This condition leads to a potential environmental problem and becomes a promising alternative as a partial replacement for Portland cement [16]. Total coal ash production in 2020 reached 7575 Mt all over the world. China was the largest coal ash producer, and it should be noted that coal ash production also grew in Russia, Indonesia, India, and Turkey. However, coal ash production decreased in the United States and the European Union [17].

The volume of plastic waste worldwide also becomes a significant concern since it has now reached 6.3 billion tonnes. Plastic waste management is still a severe problem. Most plastic waste (79%) was disposed of directly into the environment; 12% was burned; and only 12% was recycled. Plastic waste accounts for up to 80% of all marine debris, and an estimated 4.8–12.7 million metric tons are released into the oceans yearly. Generally, the best action in plastic waste management is to increase the reuse and recycling of plastic so that it has significant environmental and economic benefits [18, 19].

Fly ash, a main waste product from coal combustion, has become the interest of many researchers due to its potential for environmental problems but offering improved properties for concrete construction [20–23]. Previous researchers have reported that the use of fly ash in SCC production shows a positive effect in terms of its fresh and mechanical properties. The use of fly ash can increase the workability of fresh concrete with an optimum replacement of 15% [10, 20] and provide maximum compressive strength with a replacement of 15% fly ash [24]. However, some reports that cement replacement with fly ash for SCC is achieved by using 8% of the weight of cement [25], and a researcher also reported that cement substitution with fly ash caused a continual decrease in the compressive strength test [26].

Previous researchers have also attempted to reduce environmental problems while improving the mechanical characteristics of concrete by adding plastic fibers to the concrete mix. The facts and data show that polyethylene terephthalate waste is one of the enormous plastic wastes widely used in beverage and food packaging. However, this material is potent enough to be used as a construction material. It has a tensile strength of up to 60 MPa and an elastic modulus of up to 1 GPa. It offers good durability with insignificant mechanical strength changes; therefore, it can be utilized for materials in building material production [27–31]. Thus, PET waste has great potential to be used as a fiber admixture to improve the physical and mechanical properties of concrete and, at the same time, minimize environmental impacts.

Experiments from many previous researchers have shown different results [32–41]. All researchers reported that adding fiber from waste materials into concrete mixes reduces the workability of the concrete. However, most researchers state that adding fiber can increase concrete's mechanical strength, especially its tensile strength. However, a researcher also reports a decrease in concrete's compressive and tensile strength due to the addition of waste fiber, especially when utilizing waste metal materials [35–36]. The addition of plastic waste fibers into the SCC mixtures without SCMs reduced the workability of the concrete, slightly increased its compressive strength, significantly increased its tensile strength, and reduced its thermal conductivity. The addition of PET waste fiber to the SCC mixture without SCMs is even reported as possible to be carried out up to 2% based on the volumetric ratio [38].

The highly variable conditions of mineral wastes result in different chemical compositions of SCM and uncertain compatibility issues that may arise. The rules governing the effect of SCM and other admixtures added to SCC mixtures need to be more consistent and require additional investigation. Following the above-mentioned factual findings, this research aims to evaluate waste materials' use as admixtures for SCC production. These waste materials are proposed to improve the characteristics of concrete. In this study, fly ash will contribute to achieving the required fresh properties of SCC mixes, while PET fiber enhances the flexural strength of concrete. Using these two waste materials aims to optimize the economic value of concrete while minimizing the negative impacts on the environment generated by waste materials. This study also conducted non-destructive testing (NDT) with an ultrasonic pulse velocity (UPV) test as an alternative method, considering that the UPV test for concrete quality assessment has been in practice for decades. Previous studies have reported a good correlation between the SCC compressive strength and UPV test results [42, 43]. However, specific studies on the application of NDT to concrete with plastic fibers having different densities and thermal conductivities compared to hardened concrete as a matrix still need to be made available, especially for the particular case of plastic fiber-reinforced SCC.

2. Materials and Methods

2.1. Materials and Mix Proportion

The concrete mixes in this study used Ordinary Portland Cement (OPC) as the binder material, which meets the Indonesian Standard SNI 15-2049-2004. Ground Calcium Carbonate (GCC), with a fineness of less than 0.150 mm and low clay content, was chosen as the inert filler fine powder due to its availability at very affordable prices. The fly ash (FA) used to develop the eco-friendly self-compacting concrete was collected from the waste of the coal power plant with a low-calcium FA (class F fly ash) conforming to ASTM C 618 that passed the 75-micron sieve. GCC was added to the mixtures as the fine powder material, and fly ash that passes no 200 sieves was used as a supplementary cementitious material. The chemical compositions of OPC, GCC, and FA can be seen in Table 1.

Table 1. Main chemical composition of fine powder materials

Material		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	$CaCO_3$	$MgCO_3$
Ordinary Portland Cement	(%)	20.73	4.96	3.55	61.55	3.16	2.01	n/a	n/a
Ground calcium carbonate	(%)	0.23	0.91	1.90	n/a	n/a	n/a	92.21	4.17
Fly ash	(%)	37.24	11.39	20.87	21.65	n/a	2.16	n/a	n/a

PET waste fiber is in the shape of longitudinal pieces with a length of 35 mm and a width of 3 mm, or equivalent to an aspect ratio value of 40. Figure 1 shows the waste materials used as admixtures in this experimental work, while Table 1 shows the composition of the main chemical compounds of the binder materials used.

(a) Fly ash

(b) PET bottle fiber

Figure 1. Waste materials for SCC admixtures

The concrete mixtures use coarse aggregate from crushed granite gravel with a density of 2.67 and a maximum aggregate size of 19 mm with a fineness modulus of 7.22. Well-graded natural sand with 2.51 density and a fineness modulus of 2.44. The coarse and fine aggregate was pre-washed and then pre-soaked to minimize aggregate impurities and ensure concrete aggregates were in the Saturated Surface Dry (SSD) condition. Figure 2 shows the results of the coarse dan fine aggregate gradation analysis.

The SCC mixtures were prepared according to the specified criteria by EFNARC [2], the proposed mix design procedures by Kheder & Al-Jadiri [3], and the proposed graphs by Widodo et al. [4]. The calculation procedure can be explained in seven steps, as follows; 1) calculate the water content (W_W); 2) determine the required cement ratio; 3) calculate the cement content (W_C); 4) determine the coarse aggregate weight (W_G); 5) estimate the volume water and total fine powder ratio ($V_W/[W_C + V_{GCC}]$); 6) calculate the fine powder volume (V_{GCC}) and its weight (W_{GCC}); 7) estimate the suitable fine aggregate based on the specific gravity (W_S). The composition of SCC mixes is presented in Table 2.

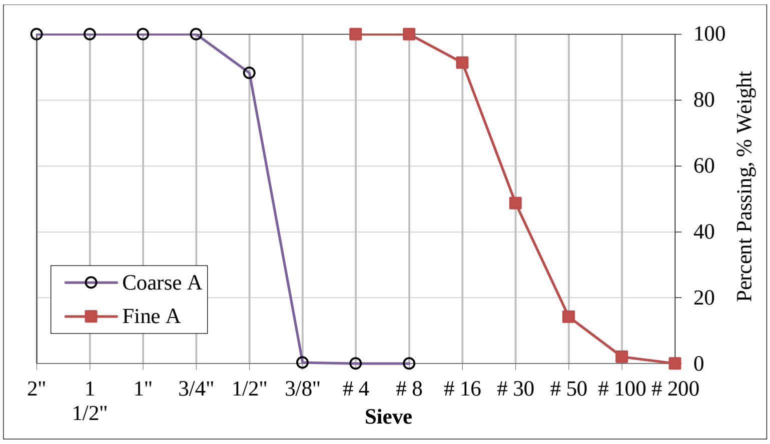

Figure 2. Gradation of the coarse and fine aggregate

Table 2. SCC Mix Proportions (kg/m^3)

Material	Variants							
	F00P00	**F15P00**	**F00P25**	**F15P25**	**F00P50**	**F15P50**	**F00P75**	**F15P75**
Water	171.5	171.5	171.5	171.5	171.5	171.5	171.5	171.5
Ordinary Portland Cement	398.8	339.0	398.8	339.0	398.8	339.0	398.8	339.0
Ground calcium carbonate	123.8	123.8	123.8	123.8	123.8	123.8	123.8	123.8
Coarse aggregate	779.0	779.0	779.0	779.0	779.0	779.0	779.0	779.0
Fine aggregate	852.8	852.8	852.8	852.8	852.8	852.8	852.8	852.8
Viscoflow (high-range water reducer)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
(ml/m^3)	931.8	931.8	931.8	931.8	931.8	931.8	931.8	931.8
Plastiment (retarder as a stabilizer)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
(ml/m^3)	502.7	502.7	502.7	502.7	502.7	502.7	502.7	502.7
Fly ash	-	59.8	-	59.8	-	59.8	-	59.8
PET bottle fiber	-	-	3.3	3.3	6.5	6.5	9.8	9.8

2.2. Details of Experimental Tests

This research begins with testing the concrete constituent materials for calculating the mix design. Afterward, prepare for mixing and testing fresh concrete properties, casting, and curing in water immersion for 56 days, and finally conduct the mechanical test. Figure 3 shows the procedure of the experimental works of this research, as presented in the flowchart below.

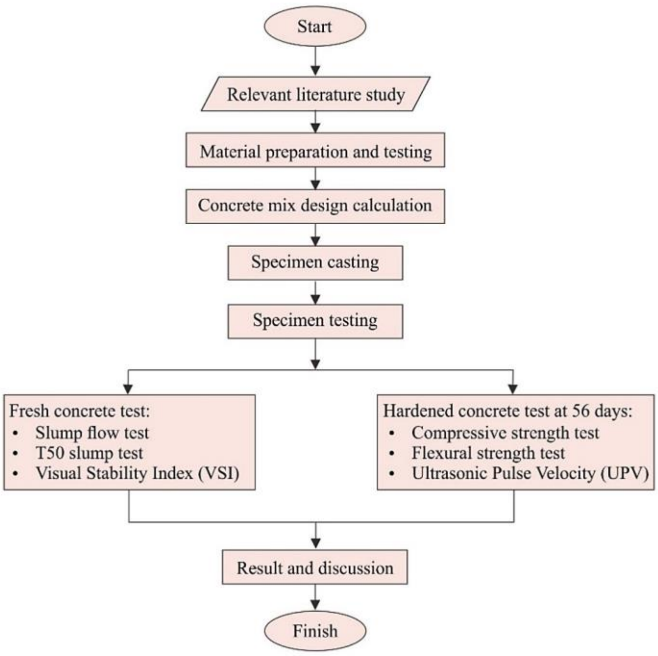

Figure 3. Flowchart of the experimental works

The workability of fresh concrete mixtures was evaluated, including their ability to spread, viscosity, and stability assessed using the test method conducted according to ASTM C1611. The mixing of eight SCC variants was carried out in a concrete mixer on the same day for each variant. Before casting, the properties of fresh concrete were evaluated based on its slump flow, T50, and VSI. Fresh SCC was cast into the molding without additional vibration or conventional compaction. After 24 hours, the specimens were de-molded and put in for water immersion for 56 days before the mechanical tests. Figure 4 shows the schematic procedure of the tests.

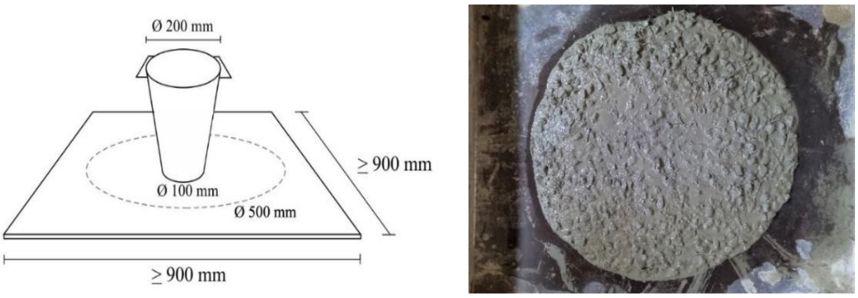

Figure 4. Slump flow test according to ASTM C-1611

Hardened concrete properties were evaluated using a non-destructive test (NDT) technique with ultrasonic pulse velocity, compressive, and flexural strength. The concrete cylinders were tested using a compression testing machine according to ASTM C-39. The compressive tests were conducted on five cylinders with a standard dimension of 150 mm x 300 mm in diameter by length, as illustrated in Figure 5. The compressive strength was then calculated as the average of those five cylinders.

Figure 5. Concrete Compression Test Set up

The flexural strength test was carried out on five beams for each concrete variant in this research. It was conducted based on ASTM C-78 using a simple beam with a four-point bending test. As described in the ASTM C-78, the flexural strength was performed on rectangular concrete beams with dimensions of 150 × 150 × 700 mm to determine the modulus of rupture, as shown in Figure 6.

The non-destructive test was conducted using the UPV test technique and carried out on five cylinders with a diameter of 150 mm and a length of 300 mm. Each cylinder was tested for five times measurements to collect ultrasonic wave velocity measurement data, as shown in Figure 7.

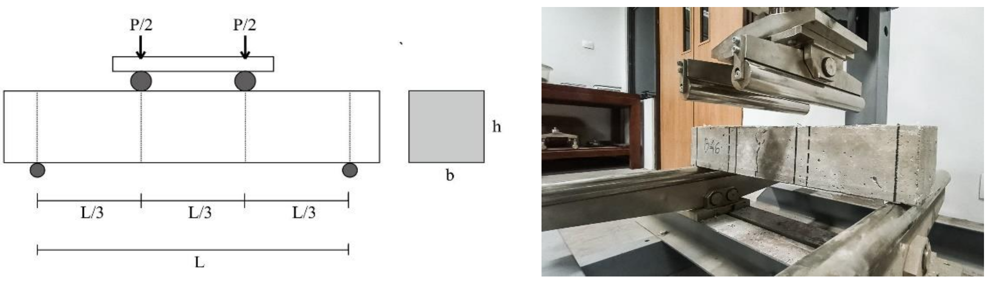

Figure 6. Concrete Flexural Test Set up

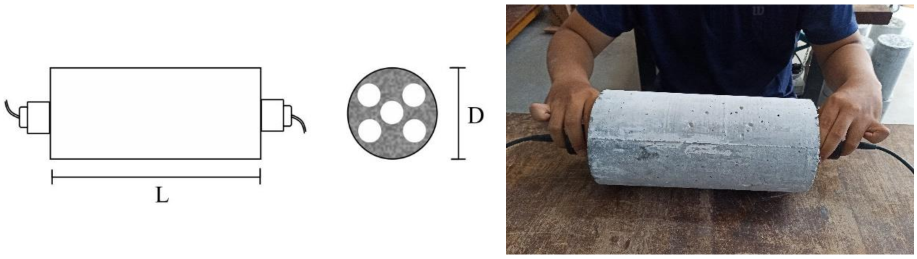

Figure 7. Ultrasonic Pulse Velocity Test Set up

3. Results and Discussion

3.1. Experimental Results

Experimental tests on fresh concrete were conducted right after each concrete mixing, including measuring the slump flow diameter along with the determination of the T50 value and making observations of the Visual Stability Index, as specified in ASTM C1611. After 56 days, the experimental works were followed by testing for the hardened concrete test. The tests included compressive strength based on ASTM C-39, flexural strength as specified in ASTM C-78, and the velocity of ultrasonic wave propagation that was observed using a display unit of the portable unit non-destructive test instrument as explained in ASTM C-597. In detail, Table 3 shows the average of all the completed test results in fresh and hardened states.

Table 3. Test results

Mixture type	Slump flow (mm)	T50 (seconds)	Visual Stability Index	Compressive strength (MPa)	Flexural strength (MPa)	Ultrasonic pulse velocity (m/s)
F00P00	596	2.84	0	43.71	3.97	4990
F15P00	578	3.00	0	45.27	4.36	5095
F00P25	567	3.48	0	43.24	4.08	4844
F15P25	570	3.28	0	41.90	4.38	4858
F00P50	555	3.63	1	41.21	4.14	4745
F15P50	544	3.70	1	36.83	4.41	4794
F00P75	510	4.25	2	41.42	4.90	4735
F15P75	519	4.70	2	36.70	4.56	4774

3.2. Test Results of Fresh Concrete

The fresh state characteristics of SCC mixtures were measured based on their slump flow diameter, T50, and the Visual Stability Index (VSI) value observed based on the guidance of ASTM 1611. Test results of the fresh state of each SCC variant are presented in Table 3, Figure 8 for the non-fly ash mixes type, Figure 9 for the mixes with fly ash addition, and Figure 10 for both variants. Figure 8 shows that the presence of waste PET fiber led to a decrease in slump flow diameter in the SCC mixtures without any fly ash addition. The same indication can also be observed in the SCC mixtures with fly ash utilized as a partial replacement for the Portland cement, as shown in Figure 9. The higher percentage of PET fiber resulted in a decrease in the value of slum flow. The reduction of fresh SCC's workability can be well explained by the presence of PET fiber, which leads to a blocking effect that impedes the ability of the concrete to flow due to its self-weight on the fresh concrete mixtures. Hence, the slump flow tends to decrease.

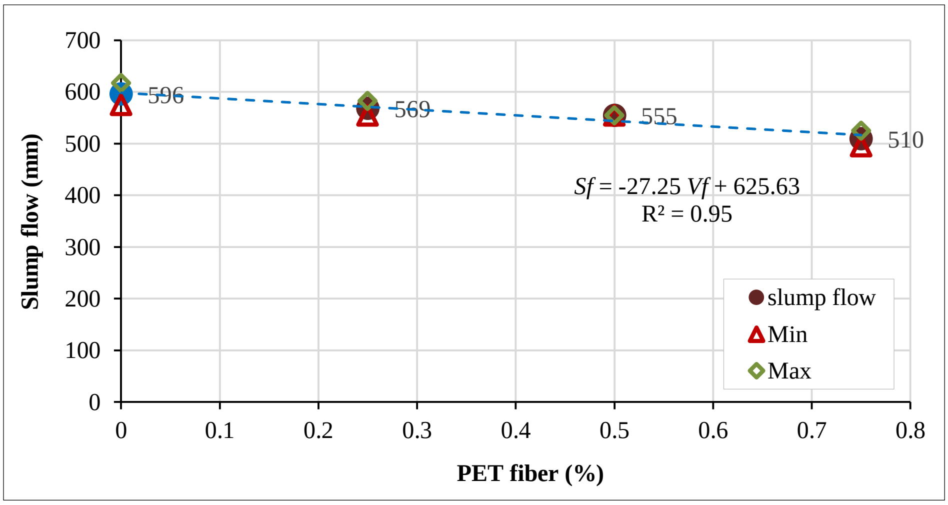

Figure 8. Effect of PET fiber on the slump flow of fresh SCC without fly ash

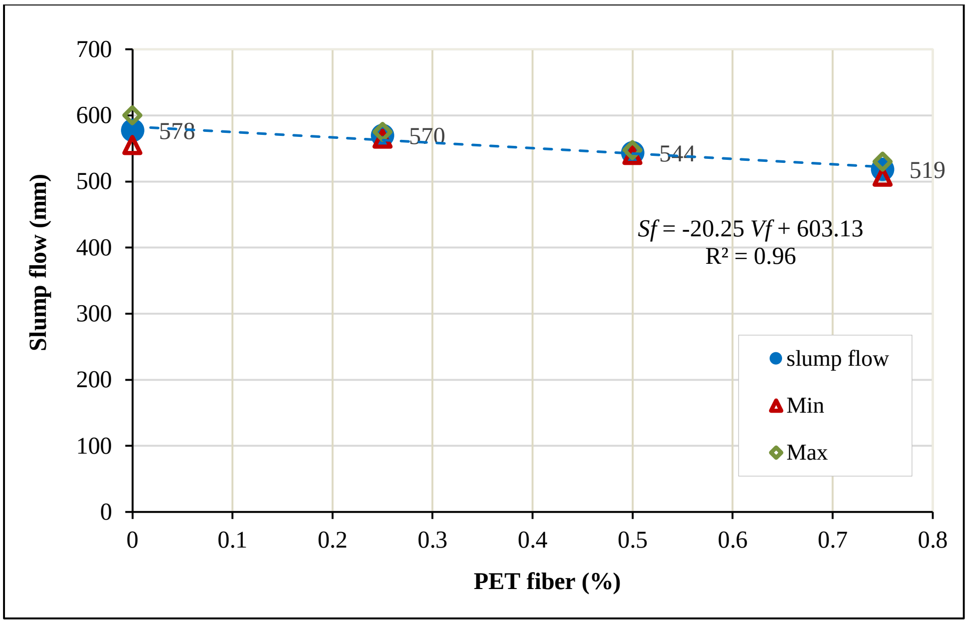

Figure 9. Effect of PET fiber on the slump flow of fresh SCC with fly ash

Figure 10 shows that partial replacement by 15% of Portland cement weight with fly ash reduces the slump flow value in fresh concrete compared to the variant that was not added with PET waste fiber. However, SCC with fly ash does not significantly differ from the slump flow diameter of fresh concrete without fly ash addition when PET fiber was added into the mixes. This condition indicates that PET fiber has more influence on the workability of SCC. The blocking effect arose from the presence of fiber which inhibits the flowability of fresh concrete.

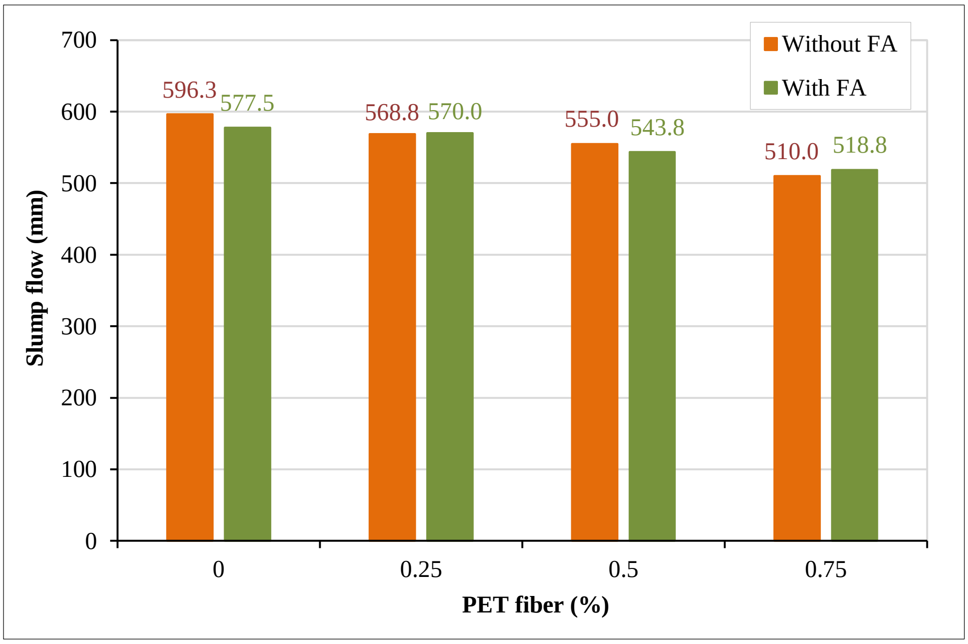

Figure 10. Effect of fly ash on the slump flow test results of fresh SCC with PET fiber

The T50 values of each SCC variant are presented in Figure 11 for the non-fly ash mixtures, Figure 12 for the fly ash added mixtures type, and Figure 13 to show the comparison of both non-fly ash and fly ash added variants. Figure 11 shows that the presence of waste PET fiber affects the increased measured T50 in the SCC mixtures without any fly ash addition. The increase of measured T50 can also be clearly observed in the SCC mixtures with fly ash as a partial replacement for the Portland cement, as shown in Figure 12. Due to the addition of PET fiber, it takes a longer time for fresh concrete to reach the 50 cm diameter limit. The reduction of fresh SCC flowability indicates that the presence of PET fiber causes a blocking effect on fresh concrete. This condition led to the flowability reduction and, consequently, the T50 increases (Figure 13).

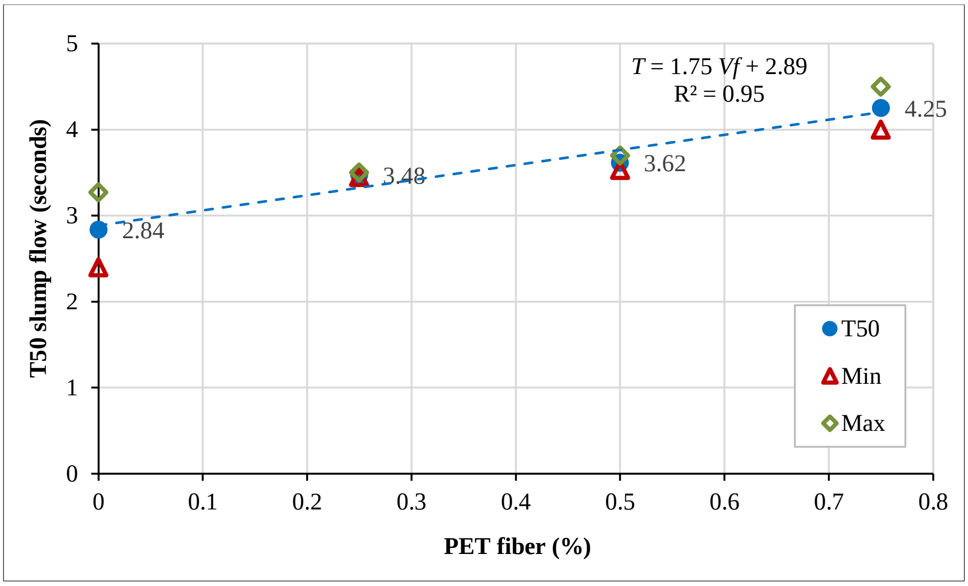

Figure 11. Effect of PET fiber on the T50 of fresh SCC without fly ash

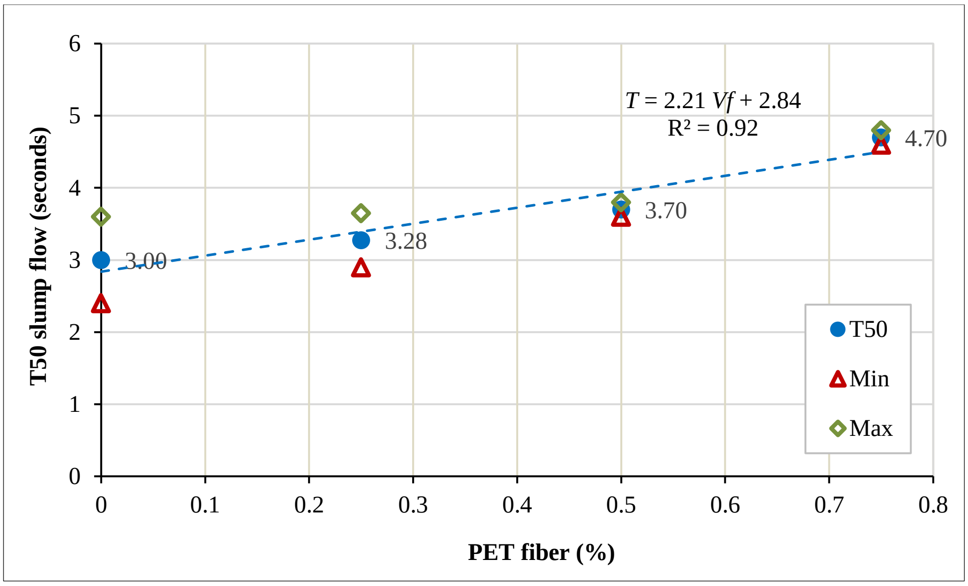

Figure 12. Effect of PET fiber on the T50 of fresh SCC with fly ash

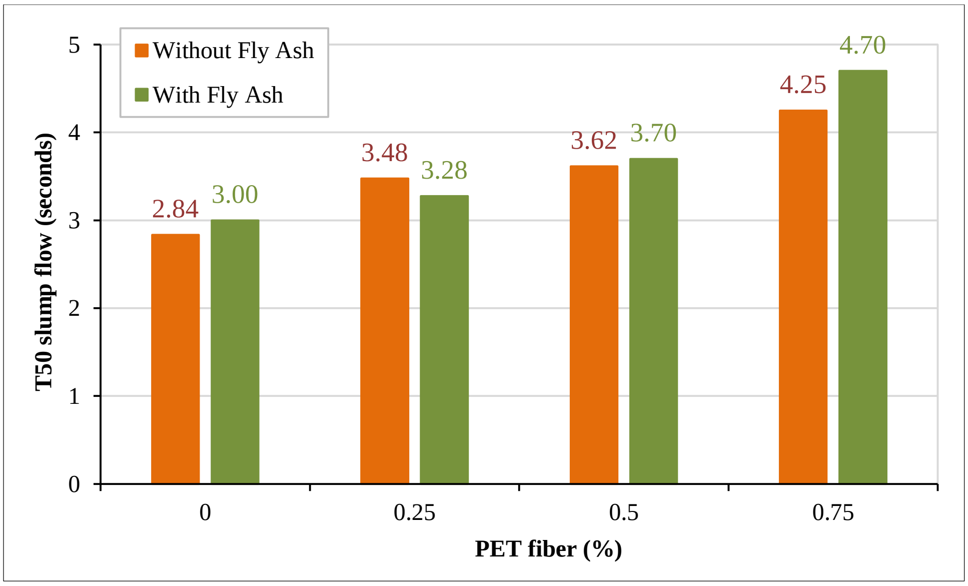

Figure 13. Effect of fly ash on the T50 test results of fresh SCC with PET fiber

3.3. Test Results of Hardened Concrete

The compressive strength test results showed a decrease due to the addition of PET fibers into the SCC mixture. The test results are shown in Figures 14, 15, and 16. PET fiber addition in SCC concrete mixes with no-fly ash showed a relatively insignificant decrease in compressive strength. SCC with no-fly ash and without PET addition reached a compressive strength of 43.71 MPa. It gradually decreased to 43.24 MPa when the mixture was added with 0.25% PET fiber, 41.21 MPa on 0.50% addition of PET, and 41.42 MPa when using 0.75% PET fiber, respectively, as shown in Figure 14. The test results show that the most considerable compressive strength reduction is 5.72%.

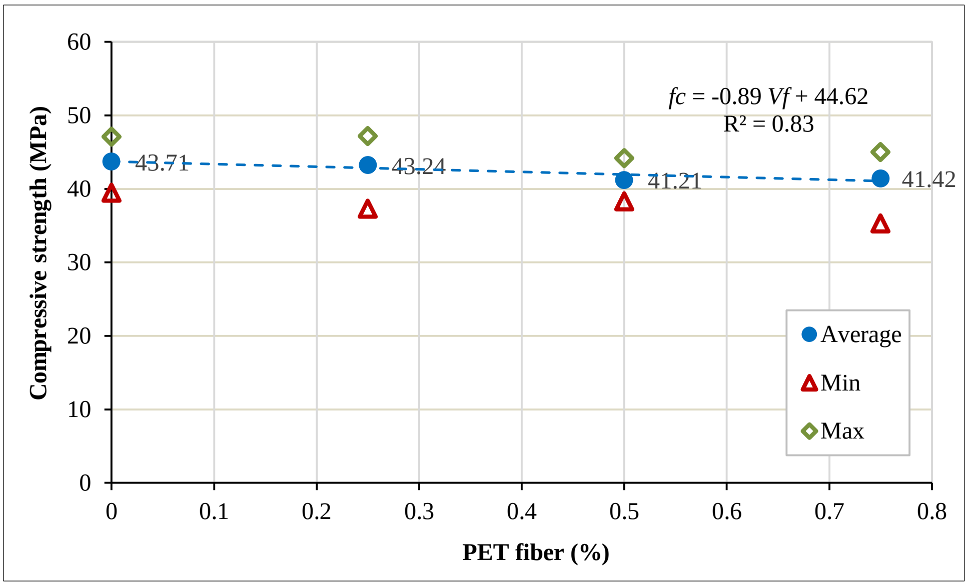

Figure 14. Effect of PET fiber on the compressive strength tests of SCC without fly ash

Figure 15 also shows a decrease in the compressive strength test. The decrease in the compressive strength of SCC with PET fiber and with the fly ash addition is more significant than the decrease in the compressive strength of the SCC mixtures with no fly ash addition. The compressive strength in the SCC variant with fly ash but without any PET fiber obtained 45.27 MPa, then decreasing successively to 41.90 MPa when the 0.25% PET fiber was added, 36.83 MPa at 0.50% PET addition and finally lowered to 36.70 MPa at 0.75% PET fiber addition. The compressive strength reduction for SCC with fly ash is reaching 18.93%. The compressive strength reduction of SCC with PET fiber was possibly caused by a blocking effect, so that the flowability of the concrete was reduced and the tendency for segregation was increased. The use of fly ash further reduces the compressive strength of SCC added with PET because of the water absorption characteristics of the fly ash that cause the free water content reduction in the concrete mixes. The presence of fly ash increases the viscosity and reduces the flowability of fresh concrete, so that the compaction ability of SCC using its weight decreases significantly. It can be confirmed by the test results of fresh concrete, which show that the addition of PET causes a decrease in the slump-flow value and increases the T50 time (Figure 16).

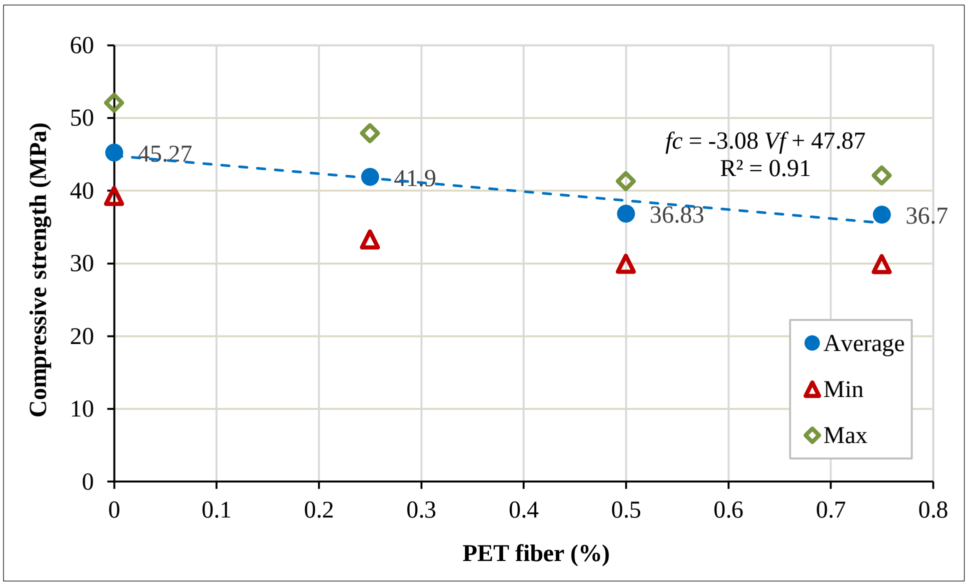

Figure 15. Effect of PET fiber on the compressive strength tests of SCC with fly ash

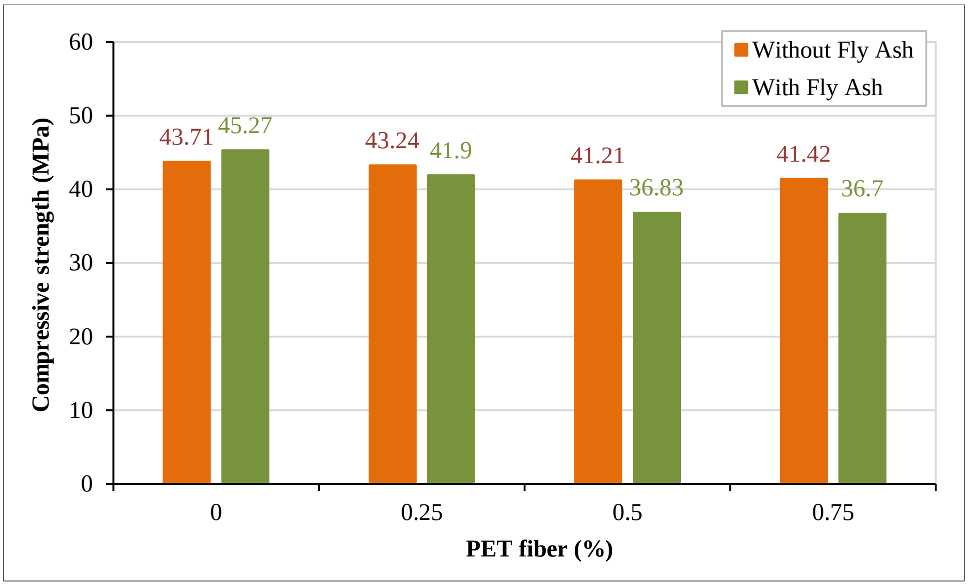

Figure 16. Effect of fly ash on the compressive strength tests of SCC with PET fiber

The flexural strength test results showed that adding PET fiber into the SCC mixtures could increase the flexural strength of the concrete beams. SCC variants without any fly ash addition showed an increase in flexural strength up to 23.43%. SCC without fly ash and PET has a flexural strength of 3.97 MPa and then increases to 4.08 MPa with 0.25% PET addition, 4.14 MPa with 0.50% of PET fiber, and finally, the highest is 4.96 MPa when the mixture utilizing 0.75% PET fiber. Detail of flexural test results on the SCC without the fly ash variant can be observed in Figure 17. The enhancement in flexural strength can be achieved because the presence of PET fiber can resist the propagation of cracks that arise due to the presence of the bending moment in the concrete beam test. It provides the energy-absorbing mechanism by bridging action to distribute macro-cracks that appear due to applied external force.

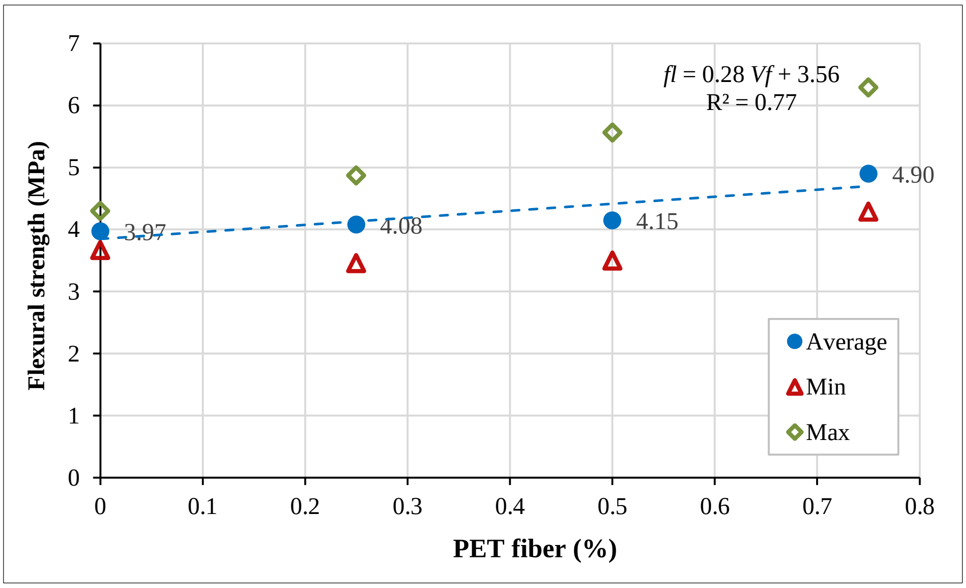

Figure 17. Effect of PET fiber on the flexural strength tests of SCC without fly ash

The increased flexural strength due to the addition of PET fiber into the SCC mixture can also be observed in the SCC with the fly ash admixture, as shown in Figure 18. SCC variant with fly ash but without PET addition resulting in a flexural strength of 4.36 MPa, then increased successively to 4.38 MPa on 0.25% PET fiber addition, then 4.41 MPa with 0.50% PET fiber, and 4.56 MPa with 0.75% PET fiber addition. Figure 18 shows that the flexural strength improvement in the SCC mixtures with fly ash addition is less significant when compared to the SCC without any fly ash addition. The increase of flexural strength due to the addition of PET fiber for the SCC variant with fly ash only reached 4.59%. Figure 19 also shows that the increased flexural strength of the SCC variant with fly ash and the PET fiber is relatively smaller than the SCC variant without fly ash. The fly ash causes absorption of some of the free water content, and the PET fiber blocks the flow of the fresh concrete so that the concrete self-compacting ability is reduced and finally causes a not maximal increase in the flexural strength test results.

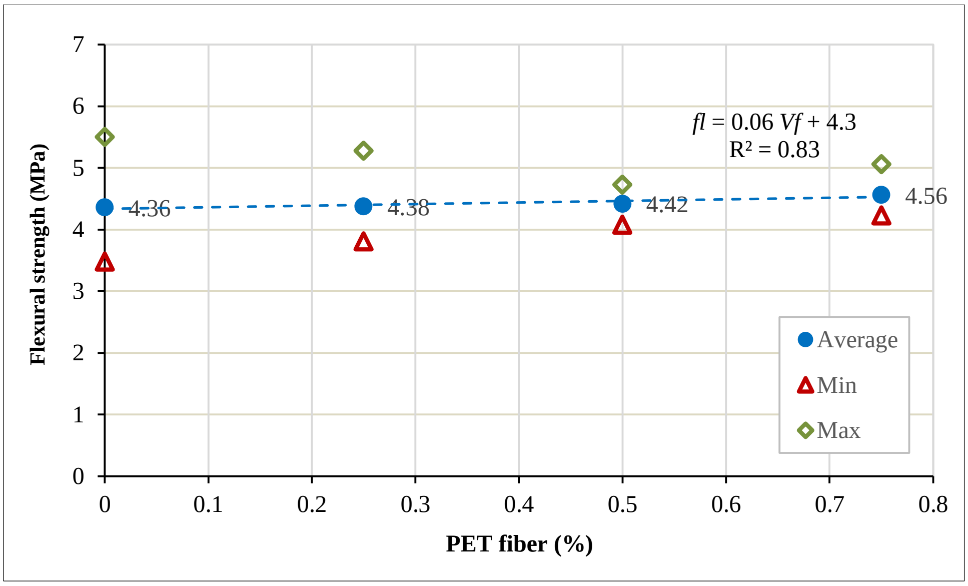

Figure 18. Effect of PET fiber on the flexural strength tests of SCC with fly ash

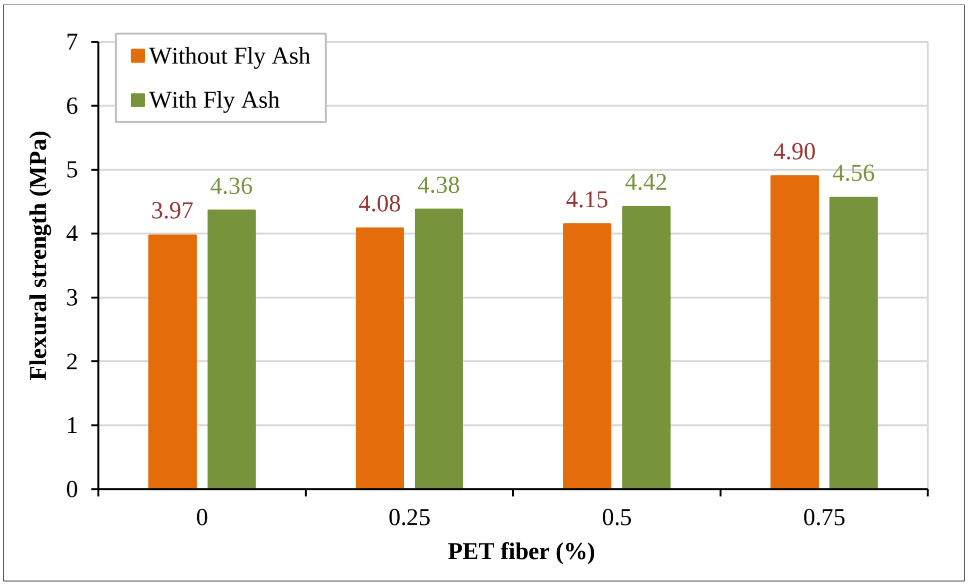

Figure 19. Effect of fly ash on the flexural strength tests of SCC with PET fiber

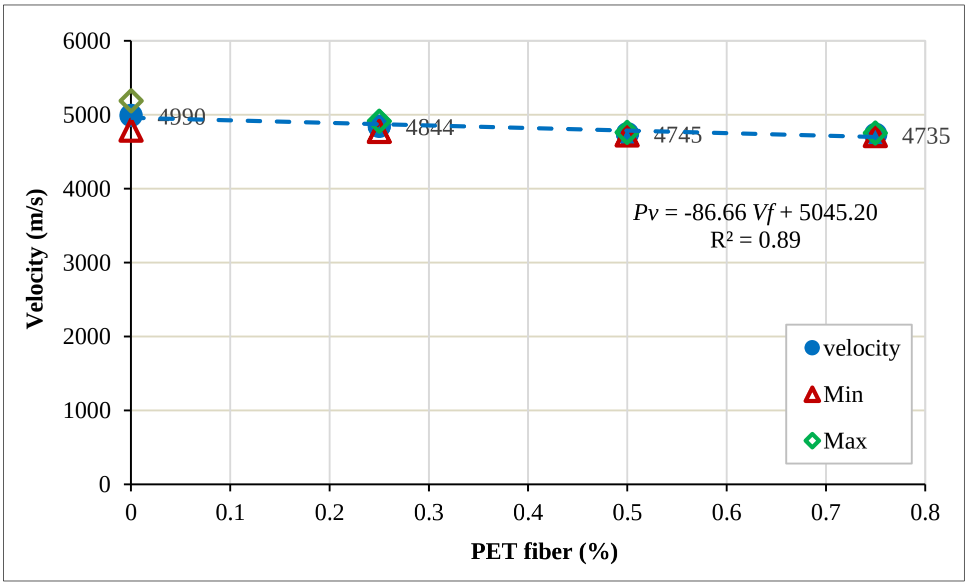

Figure 20. Effect of PET fiber on the UPV test results of SCC without fly ash

The test results showed that the ultrasonic wave propagation speed in the SCC variant without fly ash and the mixture of SCC with fly ash decreased due to the presence of PET fiber. SCC without fly ash showed a relatively insignificant decrease in the pulse velocity test. Figure 20 shows that UPV measurement of SCC without fly ash and without PET fiber resulting an average propagation speed of 4990 m/s and then decreased to 4884 m/s at 0.25% PET addition and 4745 m/s at 0.50% PET fiber and finally lowered to 4735 m/s at the use of 0.75% PET fiber. Based on the test results above, the most significant decrease in the UPV test is only 5.11%.

The decrease in wave propagation speed due to the addition of PET fibers can also be observed in the variant of SCC with fly ash, as shown in Figure 21. In the SCC variant with fly ash without PET fibers, the speed of propagation is 5095 m/s, then decreases respectively to 4858 m/s at the 0.25% of PET fiber addition, then 4794 m/s at the addition of 0.50% PET fiber and 4774 m/s at the addition of 0.75% fiber. The decrease in wave propagation speed in the SCC variant with fly ash is also relatively not significantly different, approximately 6.30%.

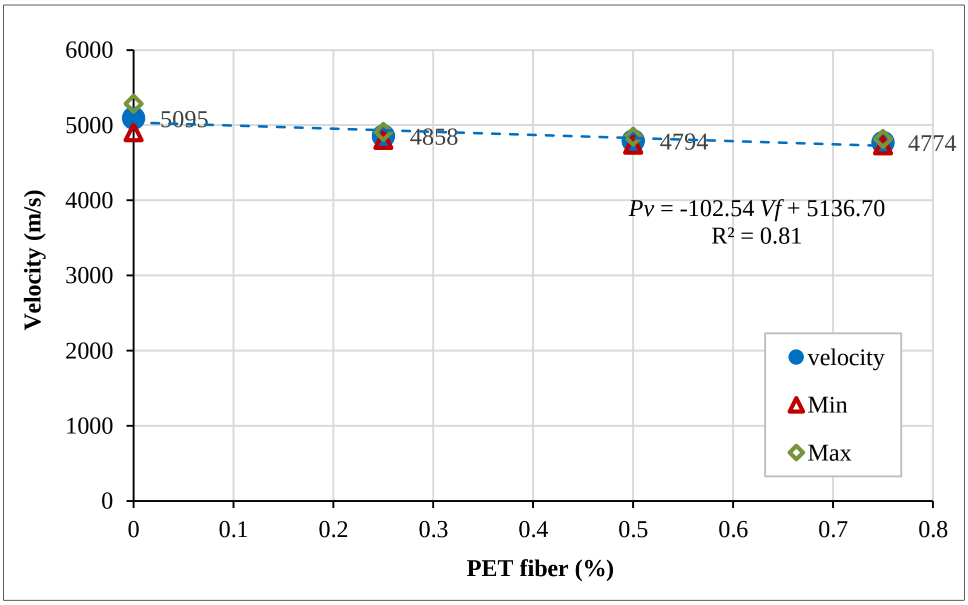

Figure 21. Effect of PET fiber on the UPV test results of SCC with fly ash

The reduction of the wave propagation velocity measured using the non-destructive technique with the ultrasonic pulse velocity test method for SCC with fly ash and SCC without fly ash variant can be observed in Figure 22. It is possible due to the slightly reduced SCC density. The SCC density slightly decreases because the concrete's ability to flow and compact under its self-weight is reduced due to the presence of PET fibers. This result is in line with the decreasing slump flow test and the increasing T50 value due to the addition of PET fiber into the fresh concrete mixes.

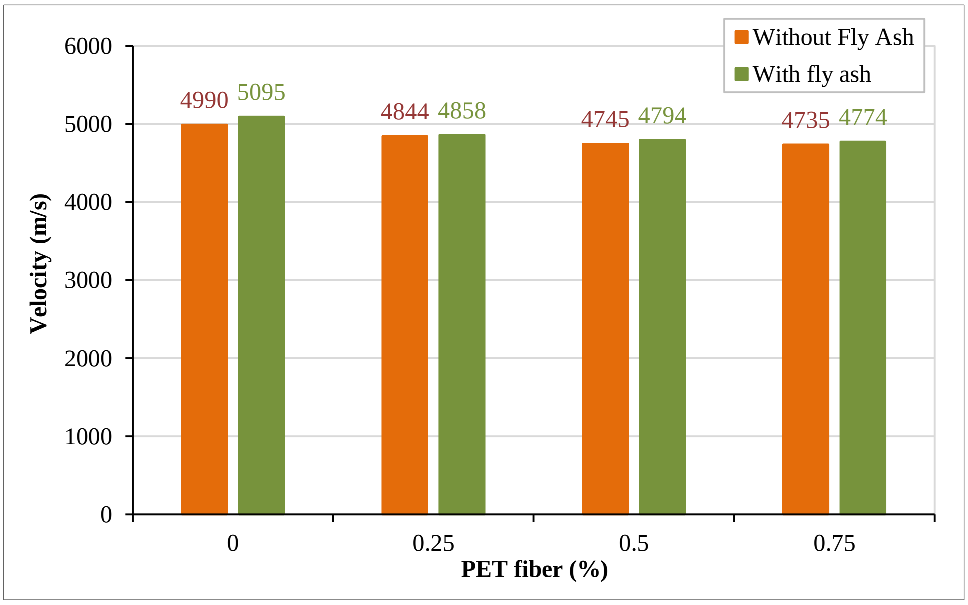

Figure 22. Effect of fly ash on the UPV test results of SCC with PET fiber

3.4. Discussions

Adding PET fibers into the SCC mix reduces the ability of fresh concrete to flow and compact independently using its self-weight. It can be identified by the decrease in their slump flow value and the increase in their T50 and Visual Stability Index. The minimum requirement for SCC fresh concrete can still be achieved by adding PET fiber up to 0.50%, both in SCC variants and with and without adding fly ash as SCM. These results align with previous researchers who stated that adding fiber and fine powder to the mixture reduces the workability and other related fresh properties of SCC production [35, 39, 40]. The decrease in the workability of concrete can be caused by the presence of PET fiber, which causes an increase in the surface area of the filler material, requiring more lubrication. It also causes a blocking effect on the concrete mixture, inhibiting its ability to flow and compact using its self-weight, and the tendency for segregation is also increasing. Adding fly ash that absorbs water from the fresh concrete will further reduce the free water content in the concrete mix so that the flowability and self-compacting ability of the SCC mixes tend to decrease.

The decrease in the concrete mixture's flowability and other related fresh properties will cause a slight reduction in its density after hardening. Therefore, the compressive strength also decreases slightly. The results are aligned with the previous researcher's findings [42]. This condition is confirmed by a decrease in the compressive strength test results for SCC in the variant with the addition of PET fiber and fly ash powder. It is caused by a blocking effect that leads to a decrease in the fresh concrete's flowability and increases its tendency for segregation. The use of fly ash reduces the compressive strength because the presence of fly ash increases the absorption of free water content in the concrete mixture. Fly ash powder increases the viscosity but reduces fresh concrete's flowability, so that the compaction ability of SCC by its weight is significantly reduced. However, the test results show that all variants with PET fiber addition in a volume fraction between 0 to 0.75% can still meet the target for average compressive strength, which is more than 40 MPa. However, for the variant with the addition of fly ash and PET fiber, the designed compressive strength can only be achieved by adding at most 0.25% of PET fiber.

Adding PET fiber into SCC mixes without fly ash and SCC with fly ash can increase their flexural strengths. Regardless of the slight decrease in the density and compressive strength of concrete slightly decreased, the flexural strength of concrete can still increase. It is achieved because the fiber can inhibit the cracks' propagation and spread and bridge the cracks that occur due to the emergence of tensile stress in the concrete specimens, as stated by previous researchers [39, 40]. Therefore, the failure of the concrete beam with PET fiber is not concentrated in a particular location only. The failure process is different from that of the concrete beams without any fiber addition. It is reasonable since fibers are added to the concrete mixes to improve the flexibility of the concrete. It halts the onset of tension cracks or prevents the propagation of cracks so that the flexural strength of PET fiber-added SCC displays better behavior than no-fiber-added concrete. Visual observations made on the specimens after the flexure test showed very different failure patterns between concrete without PET fiber and concrete with PET fiber. Concrete without PET fiber exhibits a sudden collapse process. In contrast, concrete with PET fiber demonstrates the ability of PET fiber to distribute cracks and contribute to bridging crack propagation in concrete, as shown in Figure 23.

(a) Concrete beam without PET fiber (b) Concrete beam with PET fiber

Figure 23. Collapse mechanism in the concrete flexural test

The Non-Destructive Test results assessed using the ultrasonic pulse velocity test technique with the direct method show that the wave propagation speed decreases when the fiber is added with a more significant volume fraction. These results are in line with previous tests, which indicated that the addition of PET fibers caused a decrease in the workability of fresh concrete, thereby reducing the ability of the concrete to self-compacting, which resulted in a reduction in the density of the hardened concrete. The reduced density of concrete results in less smooth propagation of ultrasonic waves, causing a longer propagation time to reach the receiver's location from the transmitter so that the pulse velocity decreases.

The test results on the characteristics of fresh concrete, compressive strength, flexural strength, and UPV test indicate that PET fiber can be used as a concrete admixture to improve the tensile strength of concrete. PET waste fiber with an aspect ratio of 40 can be added up to 0.5% for SCC without fly ash and up to 0.25% by volume fraction for concrete with fly ash addition. Further research can be directed to study PET fiber's contribution to improving the structural elements' performance.

4. Conclusions

Using waste materials as concrete admixtures is an alternative method for producing environmentally friendly concrete with better mechanical strength and durability, thereby contributing to sustainability. This study considers SCC production by utilizing fly ash as SCM and PET bottle waste as fiber reinforcement. Based on the results of the experimental tests explained in the earlier section, several significant findings can be summarized as follows:

- Fly ash as SCM and PET bottle waste as fiber reinforcement can be utilized in producing eco-friendly SCC. Even though the addition of PET to the concrete mixes tends to decrease the slump flow value and increase the T50 and the visual stability index, it is still acceptable. The decrease in SCC workability with fly ash as SCM was more significant than in the mix without using fly ash. According to ASTM C 1611, adding up to 0.5% PET into the concrete mixture can still meet the requirements for producing SCC.

- Moreover, PET fiber tends to decrease the compressive strength of SCC. The decrease in compressive strength of SCC with fly ash as SCM and PET fiber reinforcement was more significant than the decrease in SCC without fly ash. Adding up to 0.75% PET into SCC without fly ash can still meet the compressive strength target, but for SCC with 15% fly ash as SCM, PET can only be added up to 0.25% to achieve the targeted compressive strength.

- PET fiber increases the SCC's flexural strength due to the waste PET's ability to distribute cracks and provide a bridging effect in beam concrete under bending loads. The increase in flexural strength in the SCC mixture without fly ash plus PET was more significant, reaching 23.4% compared to the variant with fly ash, which only achieved an increase of 4.6%.

- The UPV test is more suitable for predicting the compressive strength of PET fiber-reinforced SCC but is less suitable for predicting flexural strength. The presence of PET fiber reduced the measured ultrasonic wave propagation speed on SCC concrete, but the decrease was insignificant. The decrease in the ultrasonic wave propagation velocity test in SCC with fly ash and PET is slightly more significant than in the SCC mixture without fly ash.

The experimental investigations indicate the enormous potential of combining fly ash as SCM and PET bottle waste as fiber reinforcement in producing eco-friendly SCC. However, the performed tests are still limited to investigating the fresh concrete characteristics and the mechanical properties of PET fiber-reinforced SCC. In order to better understand the durability and the structural performance, further experimental works need to be conducted, observing, among other things, the durability of PET fibers in SCC, shape, aspect ratio, and other volume fractions of fibers. In addition, more detailed research can investigate the bond strength between PET fiber-reinforced SCC and the reinforcement bar, the structural element performance, and the possibility for repairing and strengthening reinforced concrete structures.

5. Declarations

5.1. Author Contributions

Conceptualization, S.W.; methodology, S.W., and R.A.; validation, S.W., and R.A.; experimental works, R.A., A.P., M.F.A., A.D., and S.W.; formal analysis, S.W., and R.A.; resources, R.A., and S.W.; writing—original draft preparation, S.W.; writing—review and editing, S.W., and R.A.; visualization, R.A.; supervision, S.W.; project administration, R.A., A.P., M.F.A., and A.D. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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